Science of the Total Environment 650 (2019) 1872–1881

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Assessing climate change impacts on stream temperature in the Athabasca River Basin using SWAT equilibrium temperature model and its potential impacts on stream ecosystem

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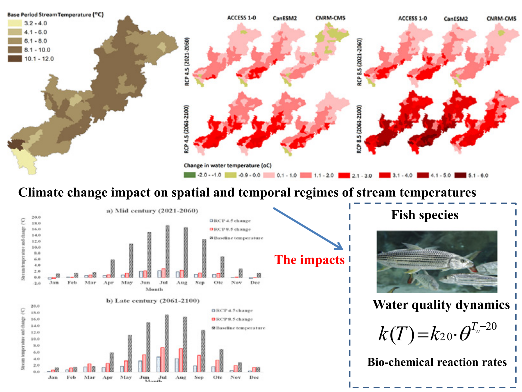
HIGHLIGHTS

- Climate change impact on the stream temperature regimes in the Athabasca River Basin was assessed.
- Stream temperatures are expected to increase in the basin due to the warmer climate.
- Stream temperature changes showed marked temporal pattern with highest increases in summer.
- Future warmer stream temperatures would affect the fish species and water quality dynamics.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 April 2018
Received in revised form 26 September 2018
Accepted 27 September 2018
Available online 27 September 2018

Editor: Ralf Ludwig

Keywords:
Stream temperature modeling
Climate change impact assessment
Equilibrium temperature approach

ABSTRACT

Stream temperatures, which influence dynamics and distributions of the aquatic species and kinetics of biochemical reactions, are expected to be altered by the climate change. Therefore, predicting the impacts of climate change on stream temperature is helpful for integrated water resources management. In this study, our previously developed Soil and Water Assessment Tool (SWAT) equilibrium temperature model, which considers both the impacts of meteorological condition and hydrological processes, was used to assess the climate change impact on the stream temperature regimes in the Athabasca River Basin (ARB), a cold climate region watershed of western Canada. The streamflow and stream temperatures were calibrated and validated first in the baseline period, using multi-site observed data in the ARB. Then, climate change impact assessments were conducted based on three climate models under the Representative Concentration Pathways 4.6 and 8.5 scenarios. Results showed that warmer and wetter future condition would prevail in the ARB. As a result, streamflow in the basin would increase despite the projected increases in evapotranspiration due to warmer condition. On the basin scale, annual stream temperatures are expected to increase by 0.8 to 1.1 °C in mid-century and by 1.6 to 3.1 °C in late century. Moreover, the stream temperature changes showed a marked temporal pattern with the highest increases (2.0 to 7.4 °C) in summer. The increasing stream temperatures would affect water quality dynamics in the ARB by decreasing dissolved oxygen concentrations and increasing biochemical reaction rates in the streams. Such spatial-temporal changes in stream temperature regimes in future period would also affect aquatic species, thus require appropriate management measures to attenuate the impacts.

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https://doi.org/10.1016/j.scitotenv.2018.09.344

1. Introduction

Stream temperature is one of the most important factors controlling the freshwater ecosystem (Zhu et al., 2018), which affects the chemical, biological, and ecological processes and functions of watersheds (Caldwell et al., 2015). It can significantly affect the water quality as it determines the saturated dissolved oxygen (SDO) in the stream (Ficklin et al., 2013) and the biochemical reaction rates (Punzet et al., 2012). Additionally, stream temperature also affects the dynamics and distribution for aquatic species (particularly for the fishes) in the stream. For instance, the increase of stream temperature is of particular concern for aquatic species, such as Eastern Brook Trout, in the southern Appalachians of the Southeastern USA (Caldwell et al., 2015). In addition, Kwak et al. (2017) predicted that water temperature in summer in Fourchue River in Quebec, Canada will have reached or exceeded the optimal growth temperature thereby affecting the growth rates for brook trout. Climate change induced by the global warming is expected to have impacts on stream temperature patterns (Cianfrani et al., 2015; Ficklin et al., 2014; van Vliet et al., 2013), which would affect the aquatic species, especially for the fish habits and distributions (Jonsson and Jonsson, 2009; Kwak et al., 2017). Therefore, it is necessary to predict the impact of climate change on stream temperature regimes to provide useful information for guiding the water management in Athabasca River Basin (ARB), which is ecologically and economically important to the development and sustainability of northern Alberta, Canada. The impacts of climate change on water quantity and hydrological processes in the ARB have been evaluated using different hydrological models (Eum et al., 2017; Shrestha et al., 2017). These two studies indicated that the annual streamflow would increase in the ARB while the summer streamflow is likely to decrease. However, the climate change impacts on stream temperature regimes in the basin has not been investigated and reported to date.

Mathematical models are useful and powerful for stream temperature modeling and the climate change impact assessment. Among models used, the statistical models have been widely used for modeling stream temperature and assessing the climate change impact (Bustillo et al., 2014; Mohseni et al., 1998; van Vliet et al., 2011). These models are based on empirical regression relationships between stream temperatures and the meteorological parameters, such as the widely used regression models between air and stream temperatures. They can account for the impact of meteorological conditions, however, these regression models based on meteorological parameters cannot account for the impact of hydrological processes, such as surface runoff, groundwater flow and snow melt, on the stream temperature. Climate change directly alters the hydrological conditions of the watershed and thus affects the stream temperature dynamics, which these regression models are insufficient to reflect. Ignoring the impact of hydrological processes could lead to unrealistic prediction of stream temperatures when assessing climate change impact. For instance, Null et al. (2013) showed that a model prediction which is solely based on air temperature could result in different trends of stream temperature changes compared to a model that considers impacts of both hydrological and meteorological conditions. Thus, it is imperative to explicitly include the impact of hydrological processes for stream temperature modeling and climate change assessment.

Some studies have modeled the stream temperature and assessed the climate change impact using various hydrological models which consider the impacts of both the meteorological and hydrological conditions (Cao et al., 2016; Ozaki et al., 2008; van Vliet et al., 2013). In our previous studies, we incorporated equilibrium temperature approach into Soil and Water Assessment Tool (SWAT) hydroclimatological stream temperature model for stream temperature modeling (Du et al., 2018; Ficklin et al., 2012). Besides impacts from meteorological conditions, the modified model also considers the impact of hydrological processes including surface runoff, groundwater flow and snow melt runoff, which could provide a comprehensive prediction of stream temperature regimes in changing climate. Furthermore, changes in stream temperature regimes could affect the water quality dynamics; however the impacts of stream temperature changes on the water quality caused by climate change have rarely been investigated. As such, we have investigated the potential impacts on water quality in the ARB caused by the stream temperature changes in this study.

2. Materials and methods

2.1. Study area

The Athabasca River originates from the Columbia Glacier in Jasper National Park and travels about 1300 km northeast across Alberta before flowing through the Peace-Athabasca Delta into Lake Athabasca (Fig. 1). The Athabasca River is the longest river within Alberta, and is the longest undammed river in the Canadian prairies area. From the headwater, the ARB pasts the towns of Jasper, Hinton, Whitecourt, Athabasca and Fort McMurray, and is a vital resource for the plants, animals and people in this area. The area of ARB is about 159,000 km^2, which accounts for about 24% of Alberta's landmass. Forest is the dominating land cover accounting for about 82% of the whole basin area, and agriculture land (9.5%) stands at a second. Hydrological monitoring stations located in the headwaters (at Jasper), mid-river (at Athabasca) and lower-river (at Fort McMurray) have been operated by the Water Survey of Canada since the 1960s. The mean annual discharge of the Athabasca River at these three main monitoring stations is $2.8 * 10^9$ m^3, $1.4 * 10^{10}$ m^3, and $2.1 * 10^{10}$ m^3, respectively. The mean annual precipitation in the basin ranges from around 300 mm in the downstream to over 1000 mm in the headwaters (Dibike et al., 2018). The mean annual temperatures are 1.8, 5.1 and 3.5 °C in the upper, middle and lower basin, respectively (Dibike et al., 2018). The stream temperature ranges from −1.0 to 36.0 °C in the ARB based on the 2973 measurements from Environmental Canada and climate change. The main activities in the basin are forestry, tourism, agriculture, pulp mills, oil and gas extraction, coal mining, and oil sands mining. The primary fish species in the ARB include northern pike, walleye, lake white fish and burbot (Lebel et al., 2011).

2.2. SWAT hydrological and stream temperature model

The SWAT model is a widely used river basin or watershed scale model to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds over long periods of time (Neitsch et al., 2011). Simulation of the hydrology in SWAT model can be divided into land phase and routing phase. The land phase of hydrological cycle simulates water yield amount in each Hydrological Response Unit (HRU), and the routing phase models the movement of water through the channel network and other water bodies to the outlet. More detailed description of SWAT hydrological processes is available from Neitsch et al. (2011).

The SWAT equilibrium temperature model developed by Du et al. (2018) is used to simulate the stream temperature. The equilibrium temperature approach is used to model heat transfer processes at the water-air interface in the model, which reflects the influences of air temperature, solar radiation, wind speed, and stream water depth on the heat transfer process. In the first step, the temperature of the water in subbasin is calculated using a basic mixing model of the volumes and temperatures of surface runoff, lateral flow, and groundwater, and snowmelt runoff to the stream water:

$$Tw,local = \frac{(Tsnow \cdot sub\_snow) + (Tgw \cdot sub\_gw) + (\lambda Tair, lag)(sub\_surq + sub\_latq)}{sub\_wyld} \tag{1}$$

where *sub_snow* is the snowmelt runoff contribution to streamflow within the subbasin (m^3d^{-1}), *sub_gw* is the groundwater flow

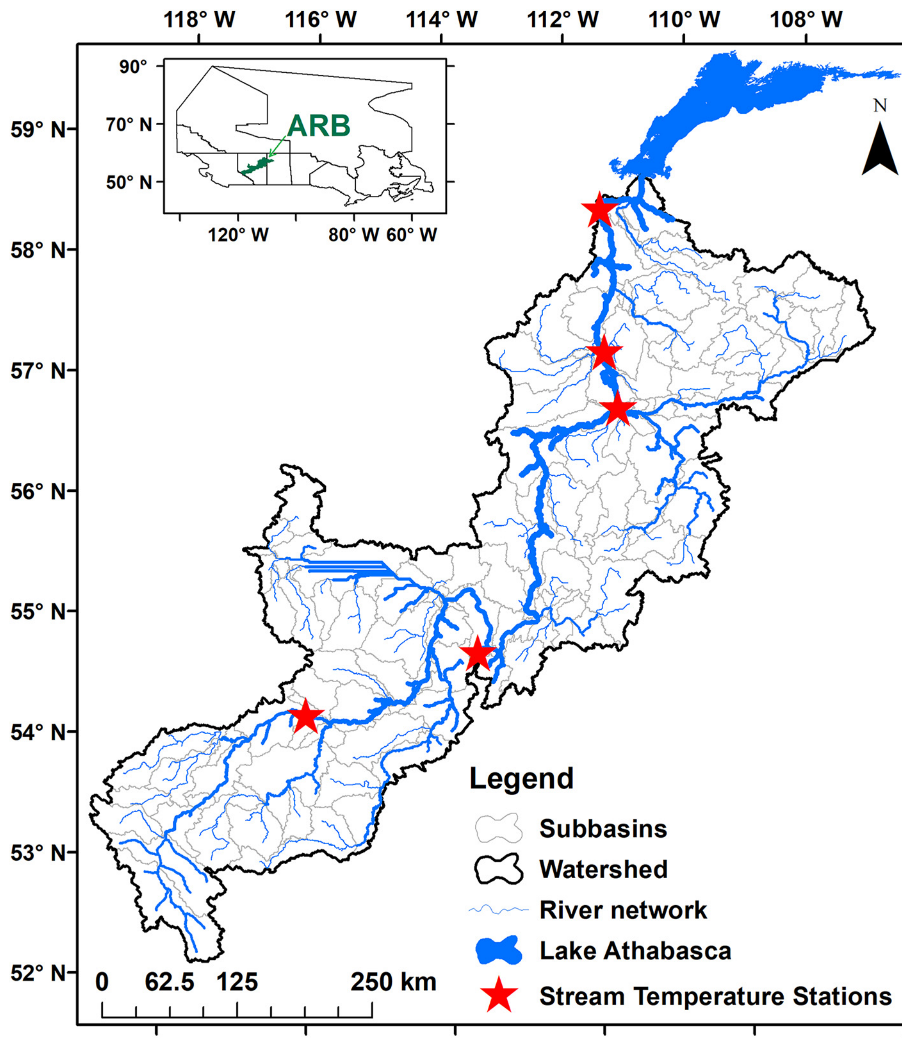

Fig. 1. Location of Athabasca River Basin with stream temperature observed stations.

contribution to streamflow within the subbasin (m^3d^{-1}), *sub_surq* is the surface runoff contribution to streamflow within the subbasin (m^3d^{-1}), *sub_latq* is the soil lateral flow contribution to streamflow within the subbasin (m^3d^{-1}), *sub_wyld* is the total water yield contribution to streamflow within the subbasin (m^3d^{-1}), T_{snow} is the temperature of snowmelt runoff (0.1 °C), T_{gw} is the groundwater flow temperature (°C), $T_{air,lag}$ is the average daily air temperature with a lag (°C), and λ is a coefficient to be calibrated.

In the second step, the initial stream temperature before the heat transfer calculation between air and water is then calculated as a weighted average of contributions within the subbasin and the contribution from the upstream subbasin(s):

$$Tw,initail = \frac{Tw,up(Qoutlet - sub\_wyld) + Tw,local \cdot sub\_wyld}{Qoutlet} \tag{2}$$

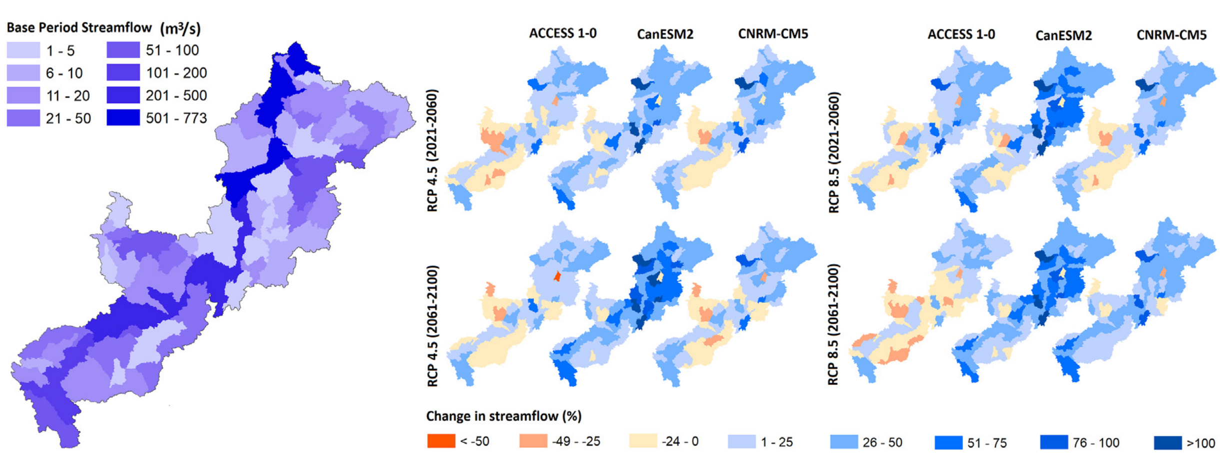

Fig. 2. Annual average streamflow changes (%) in two future periods for two emission scenarios compared to the baseline period (m^3/s).

Table 1
Annual average water balance components in mid and late century periods for two emission scenarios predicted by three climate models compared with the baseline condition.

Components	Baseline*	Mid-century		Late century	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Precipitation (mm)	510	538	549	562	579
Surface runoff (mm)	40	74	75	79	80
Sub-surface runoff (mm)	60	69	71	73	73
Evapotranspiration (mm)	378	389	397	404	424
Snow melt (mm)	127	138	137	146	138
Sub-surface/total water yield	0.60	0.48	0.49	0.48	0.48

* The values of baseline condition are from Shrestha et al. (2017).

where $T_{w,up}$ is the temperature of the streamflow entering the stream from upstream subbasin(s) and Q_{outlet} is the streamflow discharge at the outlet of the subbasin. If there is no inflow (like headwater streams), $T_{w,up} = T_{w,initial}$.

In the third step, the final stream temperature is calculated by adding a change to the initial stream temperature. The change of stream temperature can be simulated by an energy balance to account for the heat exchange between the water-air interface. Stream temperature increases or decreases with time according to the net heat flux:

$$\rho_w C_{pw} \frac{\partial T_w}{\partial t} = \frac{q_{net}}{H} \tag{3}$$

where ρ_w is the density of water (kg/m^3), C_{pw} is the specific heat capacity of water, q_{net} is the net heat flux (W/m^2) and H is the water depth (m), which is calculated by the SWAT stream routing module.

The equilibrium temperature is defined as a hypothetical water temperature at which the net heat flux is zero. The net heat input is assumed to be proportional to the difference between the stream temperature and the equilibrium temperature:

$$\rho_w C_{pw} \frac{\partial T_w}{\partial t} = \frac{K_T(T_e - T_w)}{H} \tag{4}$$

where K_T is overall heat exchange coefficient (W/m^2/°C) and T_e is the equilibrium temperature (°C).

The overall heat exchange coefficient can be calculated from the empirical relationships that include wind velocity, dew point temperature and initial stream temperature $T_{w,initial}$ (Edinger et al., 1974).

$$K_T = 4.5 + 0.05T_w + \beta \cdot f(wnd) + 0.47f(wnd) \tag{5.a}$$

$$f(wnd) = 9.2 + 0.46wnd^2 \tag{5.b}$$

$$\beta = 0.35 + 0.015\left(\frac{T_d + T_w}{2}\right) + 0.0012\left(\frac{T_d + T_w}{2}\right)^2 \tag{5.c}$$

where T_d is the dew point temperature (°C), wnd is the wind speed (m/s) as an input meteorological data of SWAT model. The equilibrium temperature can be calculated by the empirical relationship of the overall heat exchange coefficient, the dew point temperature and the solar radiation (Edinger et al., 1974):

$$T_e = T_d + \frac{slr}{K_T} \tag{6}$$

where slr is the solar radiation, which is also an input meteorological data of the SWAT model.

In the equilibrium temperature model, air temperature and an additive parameter ($T_{air} + \eta$) are used to replace the dew point temperature T_d in Eqs. (5.c) and (6), therefore the dew point temperature is not required as an input data. The η is an additive parameter, which is subject to model calibration using observed stream temperature data. The final stream temperature is corrected using the equilibrium temperature of the influence of heat transfer to the initial stream temperature by considering the water travel time in the stream TT. Combining Eq. (6) into Eq. (4) yields:

$$Tw = Tw, initial + \frac{K_T\left(T_{air} + \eta + \frac{slr}{K_T} - Tw, initial\right)}{\rho_w C_{pw} H} \cdot TT \tag{7}$$

2.3. SWAT model setup in Athabasca River Basin

The Shuttle Radar Topography Mission (SRTM) DEM data (90 m × 90 m) was used to delineate subbasins and stream networks in ARB and a total of 131 subbasins were obtained. Global Land Cover Characterization based land use map of 1 km × 1 km spatial resolution (Loveland et al., 2000) and soil map (1:1 million scale) collected from the Agriculture and Agri-Food Canada (AAFC) were also used as model spatial input datasets. For HRU definition, 11 landuse types and 320 soil types were defined and a total of 1370 HRUs were created based on the landuse, soil and slope classifications. Daily precipitation, maximum air temperature and minimum air temperature obtained from 73 stations recorded by Environmental Canada and Climate Change were used as meteorological input data to drive the model. In addition, wind speed, relative humidity and solar radiation of 230 stations recorded by Climate Forecast System Reanalysis (Dile and Srinivasan, 2014) was also used as model input.

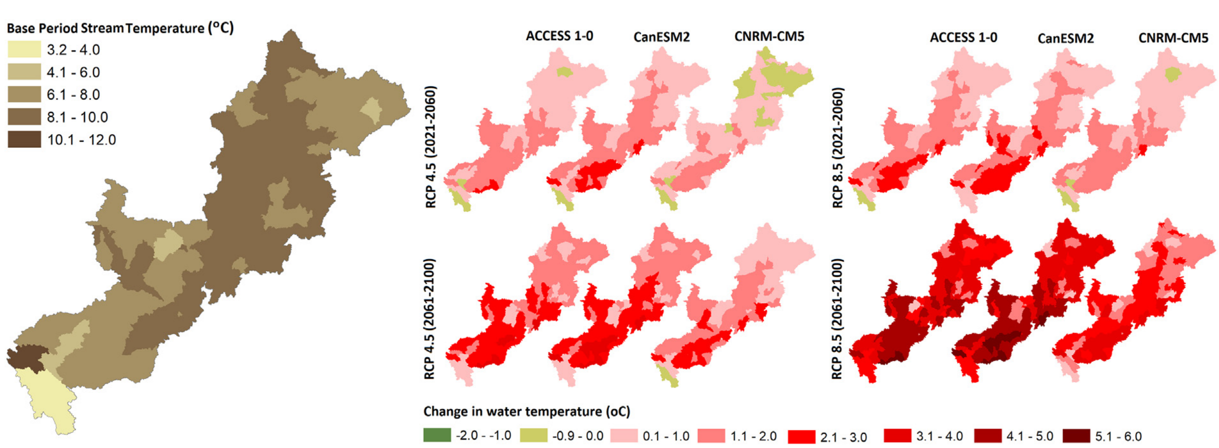

Fig. 3. Annual average stream temperature changes (°C) in two future periods for two emission scenarios compared to the baseline period.

Table 2
The predicted ranges of stream temperature changes (°C) by three climate change models at subbasin scale.

Climate models	RCP 4.5 (2021–2060)	RCP 4.5 (2061–2100)	RCP 8.5 (2021–2060)	RCP 8.5 (2061–2100)
ACCESS 1-0	−0.3–2.1	0.3–3.4	−0.1–2.6	0.8–5.4
CanESM2	−0.1–2.4	0.3–3.4	0.1–2.7	1.0–5.6
CNRM-CM5	−0.5–2.0	−0.1–2.6	−0.3–2.5	0.6–3.7

2.4. Model calibration and validation

The calibration for SWAT hydrology process is imperative to perform an accurate simulation of the stream temperature since the equilibrium temperature model considers the impacts of hydrological processes on stream temperature. The model was calibrated from 1990 to 2005 (16 years) with different conditions including both wet and dry periods. The years of 1982 to 1989 and 2006 to 2013 were used for the model validation. In addition, two years (1980–1981) warm up period were used as to minimize the impact of initial conditions on model simulations. Streamflow data of 35 stations obtained from Environmental Canada and Climate Change were used for SWAT hydrology calibration. The streamflow was calibrated in a distributed way from upstream to downstream according to the locations of the streamflow stations using the observed daily streamflow. Specifically, the basin was divided into 35 different parameter regions based on the controlling area of the observed stations and different parameter values were optimized during the calibration process. Periodic stream temperature data collected from Environmental Canada and Climate Change was used to calibrate and validate the stream temperature simulation. The sampling frequencies of stream temperature varied from monthly to seasonal, and five stations across ARB from upstream to downstream with sampling frequency close to monthly were chosen for the model calibration. The Nash-Sutcliffe Efficiency coefficient (NSE) was chosen as the objective function for the model calibration. Moreover, the coefficient of determination (R^2) and relative error (RE) were also used to assess the model performance. The definitions of NSE, R^2 and RE can be found in Du et al. (2016).

The SWAT hydrological model was calibrated and validated using observed streamflow data at 35 stations in different parts of the ARB. The statistics values of streamflow simulation performance for the 35 stations can be found in Table S2 of Shrestha et al. (2017). The average values of RE at these 35 stations were found to be 5.3% and 12.4%, respectively, during calibration and validation period. The average values of NSE were 0.57 and 0.49, respectively, during calibration and validation period. Detailed results of the SWAT streamflow simulation performance can be found in Shrestha et al. (2017). Overall, the accuracy of streamflow results the basin suggests that the SWAT model is able to simulate the streamflow at headwaters, foothills, and prairie regions reasonably well and the model's performance at downstream parts of the boreal plain region was satisfactory (Shrestha et al., 2017). This calibrated SWAT hydrological model is then used for stream temperature calibration based on the SWAT equilibrium temperature model (Du et al., 2018).

The model parameters and calibrated values for the equilibrium temperature model can be found in Table S1. Among the parameters, η was the most sensitive parameter and it was the main parameter affecting the objective function NSE value. Other parameters (Lag, λ and λ_{kt}) were less sensitive and had less impact on NSE value, but they did, however, have an impact on the RE value. The model performance statistics of stream temperature simulations for calibration and validation period at different stations are shown in Table S2. The results of equilibrium temperature model are in good agreement with the observed stream temperature data at all five stations in the ARB. The equilibrium temperature model resulted in average NSE, R^2 and RE as 0.79, 0.82 and 9.6%, respectively, during the calibration period and

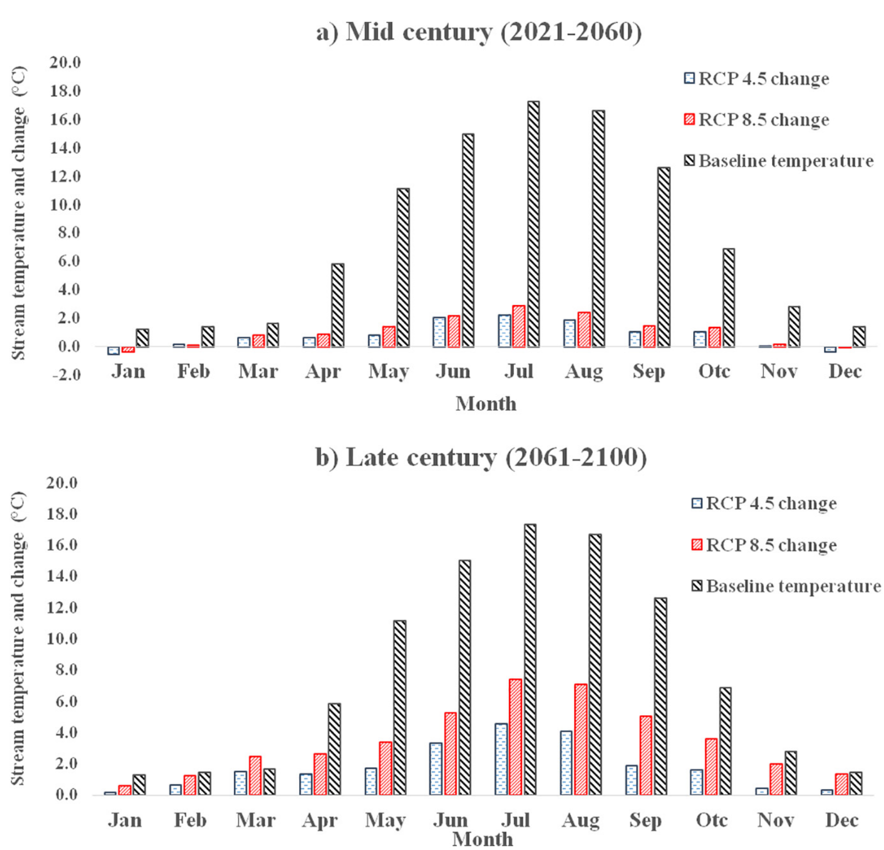

Fig. 4. Monthly average stream temperature changes (°C) in two different periods for two emission scenarios predicted by three climate models, compared to the baseline condition (°C).

Table 3
The preferred water temperature ranges and tolerance temperatures for northern pike and walleye.

Fish species	Preferred water temperature ranges (°C)	Upper tolerance temperatures (°C)
Northern pike	15.6–21.1	29.4
Walleye	18.3–21.1	27.8

0.76, 0.80 and 7.4%, respectively, during the validation period. Moreover, the equilibrium temperature showed good and consistent performances for different regions of the ARB, with NSE values all greater than 0.67. Detailed results from the stream temperature simulation performance can be found in Du et al. (2018). As the water depth was incorporated in the stream temperature simulation, the potential uncertainties associated with the algorithms used in SWAT for calculating stream characteristics like stream width could impact the stream temperature simulation and need further investigation (Du et al., 2018).

2.5. Climate change scenarios

As highlighted by Hawkins and Sutton (2009), different sources of uncertainties (e.g. climate model uncertainty, internal climatic variability and scenario uncertainty) are inherent to climate projection data. Accordingly, various researchers have attempted to include a number of climate models, different future periods and various emission scenarios or representative concentration pathways in assessing climate change impacts on hydrology and water quality (Lutz et al., 2016; Shrestha and Wang, 2018a). While we were aware of the fact that a higher number of climate models needed to be considered, we opted for three GCMs: namely -, the Center for Australian Weather and Climate Research –ACCESS 1–0, the Centre National de Recherches Meteorologiques and Cerfaces– CNRM-CM5 and the Canadian Center for Climate Modeling and Analysis – CanESM2, as they were suggested by the study of Murdock et al. (2013) as being the top three GCMs for applications in Western North America. This recommendation was based on the assessment of the accuracies of climatic projections from 26 different models that participated in the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2011). Furthermore, these GCMs are widely used by various researchers (Scinocca et al., 2016; Shrestha et al., 2017; Eum et al., 2017; Shrestha and Wang, 2018b) for climate change impact assessment in this region of Canada. At the same time, we acknowledge that more robust analyses could have been presented considering future climatic projections from a larger set of GCMs. Two commonly used IPCC AR5 emission scenarios, the Representative Concentration Pathways (RCP) 4.5 and 8.5, were used. Moreover, two time periods: a mid-century period (2040's) with a time frame of 2021–2060, and a late-century period (2080's) with a time frame of 2061–2100, were considered to evaluate the climate change impact. For this, the model simulation period (1982–2013) was used as a baseline condition. For the future climate change scenarios, the ARB was projected to have a warmer and wetter condition associated with greater amounts of precipitation and higher air temperatures based on three climate models. The mid-century mean annual air temperature is projected to change by 0.4–3.0 °C, and further increases by 1.7–5.4 °C are expected in the late-century period. As for precipitation change, increases of 3–29% and 7–34% in annual average precipitation are expected in the mid-century and late-century periods, respectively, compared with the base period. These predicted warmer and wetter trends are consistent with the previous study of this region (Eum et al., 2017).

2.6. Impact on water quality caused by stream temperature change

The impacts on water quality caused by stream temperature changes were investigated by analyzing the influences on saturated dissolved oxygen (SDO) and biochemical oxygen demand (BOD) dynamics. In SWAT model, the SDO concentration is calculated based on the water temperature in the stream (Neitsch et al., 2011):

$$SDO = \exp\left[-139.3441 + \frac{1.57501\times10^5}{Twat,K} - \frac{6.642308\times10^7}{(Twat,K)^2} + \frac{1.2438\times10^{10}}{(Twat,K)^3} - \frac{8.621949\times10^{11}}{(Twat,K)^4}\right] \quad (8)$$

where SDO is the saturated dissolved oxygen concentration (mg O_2/L) and is the water temperature in Kelvin (273.15 + °C). Besides water temperature, other factors, such as dissolved solids and atmospheric pressure, also affect the SDO concentration. In this study, the assessment for SDO concentration change is based on Eq. (8) using only water temperature as the input, which is a simplification of much more complex processes.

Since the stream temperature also affects the chemical reaction rates, the impact on BOD dynamics was investigated by assessing the impact on carbonaceous biochemical oxygen demand (CBOD) decay rate. In SWAT model, the CBOD decay rate in the stream was adjusted using an exponential equation based on simulated temperature (Neitsch et al., 2011):

$$k(T) = k20 \cdot \theta^{T_w - 20} \quad (9)$$

where $k(T)$ is the BOD decay rate at a local temperature (d^{-1}), k_{20} is the CBOD decay rate at 20 °C (d^{-1}), θ is temperature correction coefficient, and T_w is water temperature simulated by SWAT model (°C). The parameter values of k_{20} (1.71 day^{-1}) and θ (1.047) from the default values in the SWAT manual (Arnold et al., 2012) were used for this preliminary analysis. k_{20} should be calibrated using the observed CBOD data but it is sufficient to predict the change trend using the default values. However, it is a simplification of the BOD change assessments only considering the in-stream decay rate because the changes in terrestrial environment including runoff and organic matter storage will also impact the BOD dynamics in the stream.

3. Results and discussion

3.1. Climate change impact on hydrological processes

To investigate climate change impact on hydrology processes in the ARB, the annual average streamflow at subbasin scale for RCP 4.5 and 8.5 scenarios was calculated and compared with the baseline condition.

Table 4
The impacts of stream temperature on fish species base on two temperature indicators.

Indicators	Fish species	Baseline period	RCP 4.5 (2021–2060)	RCP 4.5 (2061–2100)	RCP 8.5 (2021–2060)	RCP 8.5 (2061–2100)
Number of days exceeding upper tolerance temperatures (days/year)	Northern pike	0.3	0.8	1.8	1.0	5.1
	Walleye	0.6	2.1	4.1	2.3	9.2
Number of days within the preferred temperature ranges (days/year)	Northern pike	40.2	40.1	36.0	38.2	30.3
	Walleye	17.5	21.6	20.9	21.1	18.3

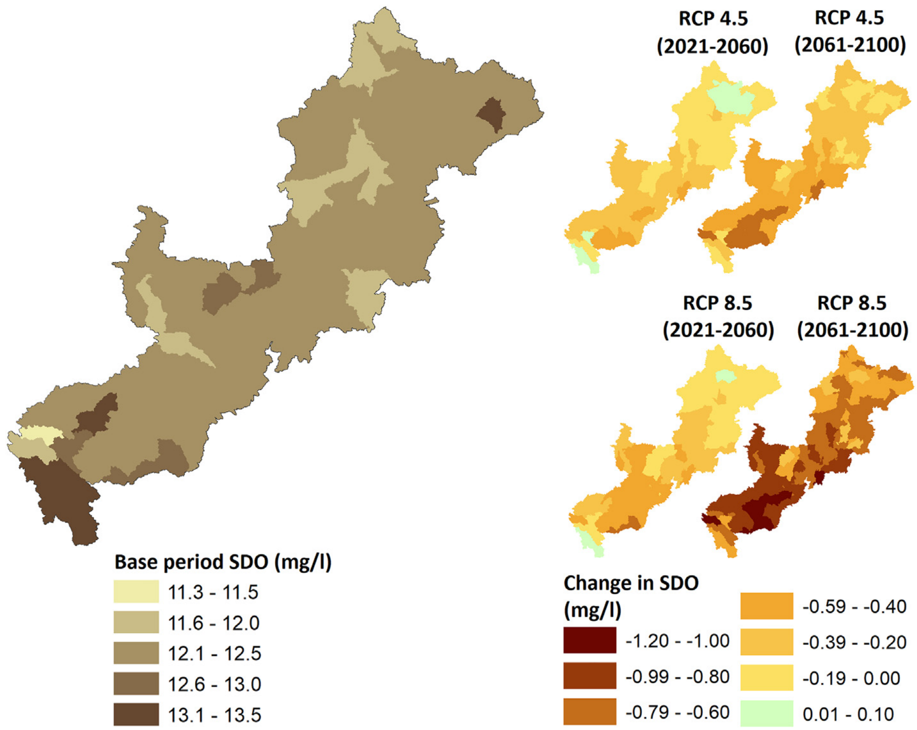

Fig. 5. Saturated dissolved oxygen change (mg/L) in mid and late century for RCP 4.5 and 8.5 scenarios.

Fig. 2 shows the streamflow change (%) in mid and late century predicted by three climate models at subbasin scale along with the baseline streamflow (m^3/s). On the basin-wide average scale, the three climate models all predicted an increasing trend of streamflow in the ARB, but the CanESM2 model predicted wetter conditions compared to the other two models. On average, the streamflow will increase by 19.0% and 23.4% in mid and late century period, respectively for the RCP 4.5 scenario. For the RCP 8.5 scenario, the streamflow will increase by 23.5% and 23.8% in mid and late century period, respectively. The results showed that the magnitudes of streamflow change vary spatially across the ARB. In general, there are moderate streamflow increases in the upper and middle parts of the ARB; however, the subbasins with streamflow decreasing trend are also located in these two parts. There are more streamflow increases in the lower part of ARB and the subbasins with more than 50% streamflow increase are mostly located in this part. In general, streamflow increases more in late century compared to

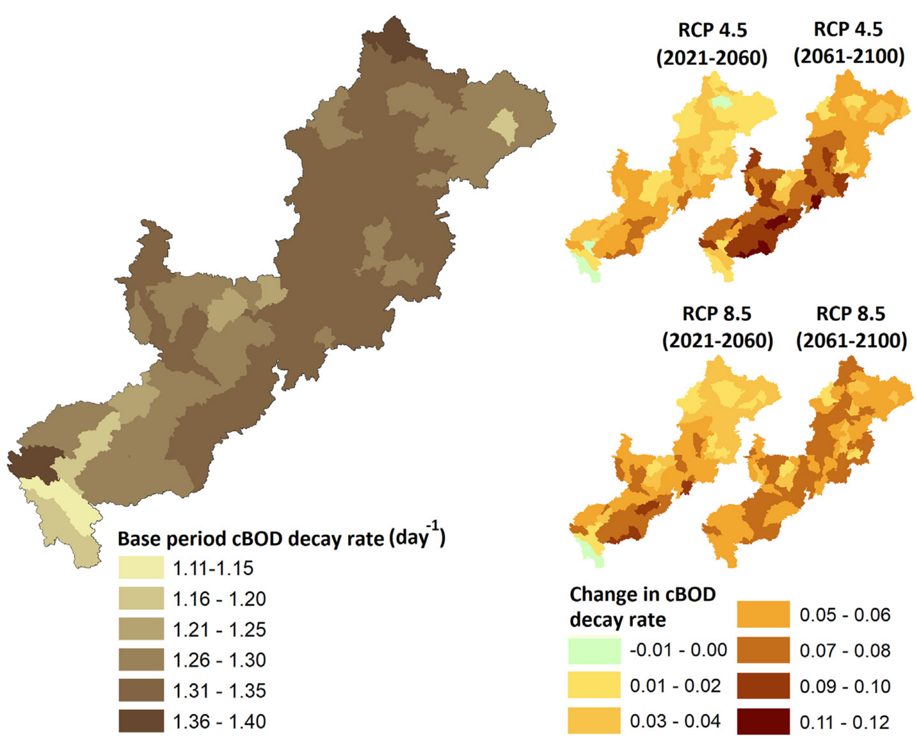

Fig. 6. Carbonaceous biochemical oxygen demand (CBOD) decay rate (/day) change in mid and late century for RCP 4.5 and 8.5 scenarios.

mid-century for both RCP 4.5 and 8.5 scenarios. Likewise, streamflow increases more under RCP 8.5 scenario compared to RCP 4.5 scenario in both mid and late century periods.

In addition, we used the mean value of water balance components predicted by the three different climate models to further investigate the impacts on hydrological processes in the basin (Table 1). On the basin average scale, the major water loss component-evapotranspiration (ET) - will increase by 5.3% to 12.2% in the future because of the warmer condition with higher air temperatures. Despite higher water loss through ET, the water yield will increase substantially (43% to 53%) due to wetter condition with more precipitation. Snow melt runoff on the basin average scale will increase by 7.9% to 15.0% compared to the baseline condition, which may decrease the stream temperature as more snow melt runoff could cool the stream temperature (Ficklin et al., 2012). For the ratio of sub-surface flow to total water yield, there will be a decreasing trend (from 0.60 to 0.48), which may increase the stream temperature as the sub-surface runoff usually has a lower temperature compared with the surface runoff.

3.2. Climate change impact on stream temperature regimes

The calibrated stream temperature model was used to run the climate change scenarios to assess the impact of climate change on future stream temperature regimes of the ARB. The annual average stream temperature changes at subbasin scale in two future periods for three different models and RCP 4.5 and 8.5 scenarios (Fig. 3) were compared with the baseline period to analyze the climate change impact. Fig. 3 showed that most of the subbasins in ARB will have warmer stream temperature compared to baseline condition but the subbasins in the headwaters will have decreasing stream temperatures, especially for the mid-century period. The stream temperature decreases in the headwater subbasin are caused by the increase of the snowmelt runoff, which cools the temperature in the streams (Ficklin et al., 2012). Also, the temperature decreases in the uppermost stream would affect the downstream temperatures, as shown when the heat balance is simulated in the equilibrium temperature model. Table 2 shows the ranges of stream temperature changes in the ARB predicted by three different climate models. In general, the predictions from ACCESS 1–0 and CanESM2 models have broader ranges compared with the CNRM-CM5 model. On the basin average scale, three different climate models all predicted warmer stream temperatures in the future. For ACCESS 1–0 model, it predicted 0.8 and 1.2 °C increases in mid-century period for RCP 4.5 and RCP 8.5 scenarios and 1.7 and 3.4 °C increases in late century period. The CanESM2 model predicted 1.2 and 1.3 °C increases in mid-century period for two different scenarios, and 1.9 and 3.7 °C increases in late century period. The CNRM-CM5 predicted the lowest stream temperature increase with 0.4 and 0.8 °C increases in mid-century period for two different scenarios and 1.2 and 2.2 °C increases in late century period. In general, the late century will have higher stream temperature compared with mid-century for both RCP 4.5 and RCP 8.5 scenarios. Moreover, the stream temperatures under RCP 8.5 scenario are higher than those under RCP 4.5 scenario for both mid and late century periods.

To further analyze the climate change impact on seasonal stream temperature regimes in the ARB, the mean value of monthly stream temperatures predicted by three different climate models in the ARB were calculated. Fig. 4 shows the predicted temperature changes of each month under RCP 4.5 and 8.5 scenarios for mid and late century, along with the baseline condition. The results showed that the stream temperatures in each month will increase in the late century but the stream temperatures in the winter in mid-century will slightly decrease by 0.03 to 0.5 °C. However, the magnitudes of temperature changes vary significantly among different months and seasons and the biggest temperature increases are found to be in summer season (June to August). Specifically, the stream temperature in the summer will increase by 2.0 to 2.9 °C in mid-century and by 3.3 to 7.4 °C in late century. Overall, the spring season will have lower temperature increases compared with summer season and the winter will have the lowest temperature increases.

3.3. Impacts on aquatic species and water quality caused by stream temperature change

On average, the climate change will alter the spatial and temporal regimes of stream temperature in the ARB. Spatially, most of the subbasins will have increasing stream temperatures but the subbasins in headwaters will have decreasing stream temperatures. Temporally, the summer season will have obvious higher temperature increases compared with other seasons. The increasing stream temperatures will affect the water quality and aquatic species in different aspects. Aquatic species usually has a specific range of temperature that they can tolerate and any changes in stream temperature may have an adverse impact on their habitats (Caissie et al., 2007). Particularly, if the average or maximum weekly stream temperature exceeds the temperature threshold, the fish species in the stream is expected to migrate or in the worst case, die (Eaton et al., 1995; Null et al., 2013). Therefore, the increases of the stream temperature in the ARB, especially such marked increases in the summer season, would have adverse impact on the fish species. Potential increases in stream temperature in the summer season can significantly affect cold water fish species (Kwak et al., 2017). Therefore, future stream temperature predictions of the summer season (June to August) were used to analyze the impact on fish species. The preferred water temperature ranges and upper tolerance temperatures for the two main species -northern pike and walleye in the ARB (Armour, 1993; Harvey, 2009) were showed in Table 3. To analyze the potential impact on the two main fish species, we calculated the mean number of days within the preferred water temperature ranges and exceeding the upper tolerance temperatures during summer season (Table 4) under RCP 4.5 and 8.5 scenarios for mid and late century based on the model averages of three climate models. During the baseline period, there were only 7 and 18 days in 30 years that exceeded the upper tolerance temperatures for northern pike and walleye. However, the numbers of days exceeding the upper tolerance temperatures would increase from 0.3 to 5.1 days/year for northern pike and 0.6 to 9.2 days/year for walleye. In addition, there will be fewer days (decreasing from 40.2 to 30.3 days/year) within the preferred water temperature ranges for Northern pike, which would have an adverse impact on the fish growth. However, the numbers of days within the preferred water temperature ranges for walleye would increase slightly in mid-century but would decrease in the later century period. Overall, the further stream temperature regimes would have adverse impacts on fish species in the ARB. Especially, the marked increasing number of days exceeding the upper tolerance temperatures will pose a potential threat to the fish species in the ARB.

For water quality, increasing stream temperatures will result in decreasing SDO concentrations based on relationship between temperature and SDO (Ficklin et al., 2013) and this also applies in the ARB. Moreover, the higher stream temperature in summer season would indicate that decrease in DO concentration would be more severe. We used the predictions from model averages of three climate models to analyze the impact of stream temperature changes on water quality dynamics in the ARB. Fig. 5 shows the SDO concentration changes (mg/L) in mid and late century for RCP 4.5 and 8.5 scenarios compare to the baseline period. The results showed that most of the subbasins will have decreasing SDO concentrations and the SDO concentrations on the basin average scale will decrease by 0.17 and 0.32 for mid and late century, respectively under RCP 4.5 scenario and 0.25 and 0.72 mg/L under RCP 8.5 scenario. The DO concentration is important to maintain aquatic life in the riverine system and a decreasing DO concentration would have adverse impact on the aquatic species. In addition, the stream temperature has direct impact on biochemical reaction rates since the reaction rates vary exponentially with the stream

temperatures. For instance, Punzet et al. (2012) investigated the impact of climate change on BOD decay rates caused by stream temperature changes at a global scale and the results showed that there are generally higher BOD decay rates, which would lead to a drop of in-stream organic loadings. The BOD decay rates will be higher due to elevated stream temperatures in the ARB especially during summer, which would consume the DO and further decrease DO concentrations in the streams. Fig. 6 shows CBOD decay rate (day^{-1}) change for mid and late century under RCP 4.5 and 8.5 scenarios based on the model averages of three climate models. The results showed that most of the subbasins will have higher CBOD decay rates and the decay rate will increase by 0.03–0.04 and 0.06 day^{-1} on the basin average scale for mid and late century, respectively. In addition, other chemical reaction rates, such as those affecting nutrient cycling in the basin, are also dependent on the stream temperature and thus the change of the temperature will change the chemical reaction kinetics in the river networks of the ARB.

4. Conclusions

SWAT equilibrium temperature model, which combines the impact of both meteorological condition and hydrological processes, was used to assess the impact of climate change on the stream temperature regimes in the ARB. Three climate models were used for the assessment and the results showed that the stream temperatures are projected to increase in most of the subbasins of the ARB on the annual average scale. On the basin average scale, annual stream temperatures are expected to increase 0.8 to 1.1 °C in mid-century and 1.6 to 3.1 °C in late century predicted by three different climate models. However, the stream temperatures in the headwaters were predicted to decrease due to the cooling effect of increased snow melt runoff. The stream temperature changes also showed a distinct temporal pattern with the highest stream temperature increases (2.0 to 7.4 °C) in the summer season. Such increasing stream temperatures will affect water quality dynamics in the ARB by decreasing dissolved oxygen concentrations and increasing the biochemical reaction rates in the streams. In addition, the increases of the stream temperature, especially the marked increases predicted in summer, would possibly impact the fish species in the ARB. The results showed that there will be many more days exceeding the upper tolerance temperatures during summer season for the two main fish species in the ARB. The marked increasing number of days exceeding the upper tolerance temperatures will pose a potential threat to the fish species in the ARB. Therefore, it is imperative to implement effective management measures to lower the impacts of stream temperature changes caused by climate change on river ecosystems of the ARB.

Acknowledgements

The authors would like to thank the Alberta Economic Development and Trade for the Campus Alberta Innovates Program Research Chair (No. RCP-12-001-BCAIP).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.09.344.

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